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Magnon condensation and spin superfluidity

Yury M. Bunkov [a], Vladimir L. Safonov [b,c,*]

[a] Kazan Federal University, Kremlevskaya 18, 420008 Kazan, Russia
[b] Mag and Bio Dynamics, Inc., Granbury, TX 76049, USA
[c] Physical Science Department, Tarrant County College, South Campus, Fort Worth, TX 76119, USA

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ABSTRACT

We consider the Bose-Einstein condensation (BEC) of quasi-equilibrium magnons which leads to spin superfluidity, the coherent quantum transfer of magnetization in magnetic material. The critical conditions for excited magnon density in ferro- and antiferromagnets, bulk and thin films, are estimated and discussed. It was demonstrated that only the highly populated region of the spectrum is responsible for the emergence of any BEC. This finding substantially simplifies the BEC theoretical analysis and is surely to be used for simulations. It is shown that the conditions of magnon BEC in the perpendicular magnetized YIG thin film is fulfillied at small angle, when signals are treated as excited spin waves. We also predict that the magnon BEC should occur in the antiferromagnetic hematite at room temperature at much lower excited magnon density compared to that of ferromagnetic YIG. Bogoliubov's theory of Bose-Einstein condensate is generalized to the case of multi-particle interactions. The six-magnon repulsive interaction may be responsible for the BEC stability in ferro- and antiferromagnets where the four-magnon interaction is attractive.

1. Introduction

Spin deviations from the magnetic order in a magnetic material (ferromagnet, antiferromagnet or ferrites) are manifested by spin waves and their quanta, magnons. Magnons are quasiparticles which represent a very useful quantum theoretical tool to describe various dynamic and thermodynamic processes in magnets in terms of magnon gas. Since magnons have magnetic moments, the external alternating magnetic field can excite extra magnons and increase the disorder in the magnetic system. However, in certain conditions, the increase of magnon density leads to a new state, so-called, magnon condensate, in which a macroscopic number of magnons forms a coherent quantum state (see, e.g., [1,2]). This macroscopic state can significantly change the properties of magnon gas, its dynamics and transport. An example is the phenomenon of quasi-equilibrium Bose-Einstein condensation (BEC) of excited magnons on the bottom of their spectrum as a single-particle long-range coherent state of quantum liquid. This state generate an uniform long-lived precession of spins formed by quantum specificity of the magnon gas when the magnon density exceeds certain critical value. The spatial gradients of this state exhibit a spin superfluidity, the non-potential transport of deflected magnetization. The spin superfluidity is an extremely interesting phenomenon for both fundamental and applied studies. It should be emphasized that the main paradigm of magnetic dynamics, the Landau-Lifshitz-Gilbert equation, does not contain complete information about the Bose-Einstein condensate of magnons. BEC is the principal result of quantum statistics and for magnons it can exist at room and even higher temperatures.

For the first time the existence of quasi-equilibrium Bose condensate was demonstrated in the experiment with nuclear magnons in the superfluid antiferromagnetic liquid crystal ^{3}He-B in 1984 [3]. The theoretical explanation of this phenomenon [4] was developed on the basis of global Ginzburg-Landau energy potential. A similar approach was later developed to explain the atomic BEC [5]. In the experiments with an antiferromagnetic ^{3}He-B, the following phenomena were observed: a) transport of magnetization by spin supercurrent between two cells with magnon BEC; b) phase-slip processes at the critical current; c) spin current Josephson effect; d) spin current vortex formation; d) Goldstone modes of magnon BEC oscillations. Comprehensive reviews of these studies can be found in Refs.[6–8]. Currently magnon BEC found in different magnetic systems: i) in antiferromagnetic superfluid ^{3}He-A [9,10]; ii) in in-plane magnetized yttrium iron garnet $Y_3Fe_5O_{12}$ (YIG) film (with two minima in the magnon spectrum) [11,12] and in normally magnetized YIG film [13]; iii) in antiferromagnets $MnCO_3$ and $CsMnF_3$ with Suhl-Nakamura indirect nuclear spin-spin interaction [14–16]. An explanation of analogy between the atomic and magnon BEC is given in Ref. [17].

* Corresponding author.
E-mail address: vlsafonov@magbiodyn.com (V.L. Safonov).

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